Satellite Remote Sensing : Wind, Surface

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1. Introduction

Sailors understand both the importance and the difficulty in getting information on wind over oceans. The textbooks still describe global ocean wind distribution in sailor's terms: the calms of the Doldrums and Horse Latitudes, the steady Trade Winds, and the ferocity of the Roaring Forties. Just a few decades ago, almost all ocean wind measurements came from merchant ships. The quality and geographical distribution of these wind reports are uneven.

Today, many citizens believe that operational numerical weather prediction (NWP) will give us all the wind information we need, until a hurricane suddenly intensifies and changes course, or the unexpected delay of monsoon brings drought, or the Pacific Trade Wind collapses before an El Niño. When prediction fails and disaster hits, then we remember that NWP depends on models which are limited by our knowledge of the physical processes and the availability of data.

Wind is a vector quantity. Spaceborne microwave scatterometers are the only proven instruments that will give us measurements of both wind speed and direction over ocean, under clear and cloudy conditions, day and night. They give us not only a near-synoptic global view, but details not possible using NWP models. Such coverage and resolution are crucial to understanding and predicting the changes of weather and climate.

The principles of scatterometry and scatterometer missions will be summarized in Section 2 and 3. Examples of scientific impact of spacebased scatterometer will be given in Section 4. The primary functions of radar altimeter, synthetic aperture radar, and microwave radiometer are not wind measurement, but they can give wind speed as a secondary product. Wind speeds are important in the own right and wind speed from these sensors can be applied with directional information derived from means. The wind speed measuring capability of these sensors are described in Section 5. Future mission and technology are summarized in Section 6.

2. Principles of Scatterometry

During the Second World War, marine radar operators observed noises on their radar screens, which obscured small boats and low-flying aircraft. They termed this noise "sea clutter". This clutter was the backscatter of the radar pulses by the small waves on the ocean's surface. The radar operators at that time were quite annoyed by these noises, not knowing that, a few decades later, scientists would make important applications.

The scatterometer sends microwave pulses to the earth's surface and measures the power backscattered from the surface roughness. The roughness may describe the characteristics of polar ice or vegetation over land. Over the ocean, which covers over three-quarters of the earth's surface, the backscatter is largely due to the small centimeter waves on the surface. The idea of remote sensing of ocean surface winds was based on the belief that these surface ripples are in equilibrium with the local wind stress. At incident angles greater than 20°, the radar return is governed by Bragg scattering, and the backscatter increases with wind speed. The backscatter is governed by the in-phase reflections from surface waves. For a smooth surface, the radar receives no return when viewing at an angle. But, as the surface roughness increases, backscatter occurs as scattering from periodic structures in the surface roughness constructively interferes. The backscatter depends not only on the magnitude of the wind stress but also the wind direction relative to the direction of the radar beam (azimuth angle). The capability of measuring both wind speed and direction is the major unique characteristic of the scatterometer.

Because the backscatter is symmetric about the mean wind direction, observations at many azimuth angles are needed to resolve the directional ambiguity. A scatterometer that measures only at two orthogonal azimuth angles, such as Seasat (see Section 3), will always includes wind solutions of nearly equal magnitude and 180° apart. Because of the uncertainties in the wind retrieval algorithm and noise in the backscatter measurements, the problem with directional ambiguity was not entirely eliminated with additional azimuthal looks in the scatterometers launched after Seasat. A median filter iteration technique initialized by the wind direction solution closest to NWP wind field has been commonly used to remove the directional ambiguity.

There is a long history of theoretical studies of the relationship between wind and backscatter, based on laboratory data. However, these theoretical or dynamic-based relationships (called geophysical model functions) were not sufficient for operational wind retrieval in open oceans. The geophysical model function, from which ocean surface wind vectors are retrieved from the observed backscatter, is largely based on empirical fits of data.

Because the capillary waves, which determine backscatter, are governed by stress, the approach of relating backscatter observations directly to measurements of surface stress have been made. The definition of the geophysical data product of scatterometer as the equivalent neutral wind is based on the same reasoning. The backscatter has also been related to pressure gradient or geostrophic winds, which may be more coherent over the scatterometer footprint than surface winds.

While wind is the primary factor in the changes of backscatter measured by a scatterometer, other secondary factors, such as sea surface temperature (SST), rain, surface film, atmospheric stability, sea state and surface current may also affect scatterometer measurement, and may cause errors in wind retrieval. With the increasing accuracy of scatterometer wind measurement, understanding and quantifying such effects is becoming increasingly important and have become scientific fields in their own right.

3. Scatterometer Missions

Historically, scatterometers of the European Space Agency (ESA) used the C-band (5 GHz), but the National Aeronautics and Space Administration (NASA) prefers the Ku-band (14 GHz). A higher frequency is more sensitive to shorter surface waves. The Ku-band is more sensitive to wind variation at low winds but is more subjective to atmospheric effects and rain contamination. Five scatterometers have been launched on polar-orbiting satellites and their major characteristics are summarized in Fig. 1.

NASA launched a scatterometer on the Seasat Mission in June 1978. Four fan-beam, dual-polarized antennas, oriented at 45° and 135° to the spacecraft subtrack, illuminated two 500-km swaths, one on each side of the spacecraft, providing wind vectors at 50-km resolution. However, only one side was in operation most of the time, covering less than 40% of the global ocean daily. The incident angle varies from 25° to 55°. The accuracy of the backscatter is about 0.7 db. The two orthogonal azimuth angles were not able to resolve the wind direction unambiguously. Seasat failed in October 1978.

A scatterometer was launched by ESA on the first European Remote Sensing (ERS-1) Satellite in August, 1991, and it was followed by an identical instrument on the ERS-2, which was launched in April 1995 and put into operation in 1996. The ERS scatterometers scan a 500-km swath on one side of the satellite, and measure at three azimuth angles, 45°, 90°, and 115°, with vertical polarization only. They provided winds over only 41% of the global ocean daily. The incident angle varies from 22° to 59° for the fore and aft beams and from 18° to 51° for the mid-beam. The backscatters have 50-km spatial resolution but are sampled at 25 km.

The NASA Scatterometer (NSCAT) was launched in August 1996 on the first Japanese Advanced Earth Observing Satellite (ADEOS), which was later renamed Midori. The six fan-beam antennas provide 600-km swaths on both sides of the spacecraft, covering 77% of the global ocean at 25-km resolution daily. The accuracy of backscatter is 0.2 db. The antennas made observations at 45°, 115° and 135° azimuth angles. The fore and aft beams measure only at vertical polarization, with incident angle varies from 22° to 63°, while the midbeam measures at both vertical and horizontal polarization with incident angle varies from 18° to 51°. The unexpected destruction of the solar array caused the early demise of NSCAT, after it had returned nine months of data.

NASA launched QuikSCAT, a Ku-band scatterometer with a new design, in 1999. It uses pencil-beam antennas in a conical scan and has a continuous 1,800-km swath that covers 93% of the global ocean in a single day. The standard wind product has 25-km spatial resolution, but special products with 12.5-km resolution have been produced for selected regions. It measures horizontally and vertically polarized backscatter at 46° and 54° incident angles respectively.

4. Major Applications

One of the basic applications of scatterometer wind measurement is in predicting weather. Although the ERS-1 scatterometer was launched in 1991, the data were not operationally assimilated into NWP until 1994. All major weather forecast centers in Europe, Japan, and the U.S. implemented the assimilation of ERS scatterometer winds between 1994 and 1997. NSCAT had only a short life span; the spacecraft failed before any NWP center could set up the system to assimilate its data. QuikSCAT has been in operation for two years, and the European Center for Medium Range Weather Forecast has just begun operational assimilation of the data. A recent comprehensive impact study of NSCAT revealed an approximately one-day extension of useful forecast skill in the Southern Hemisphere. The impact of assimilation of NSCAT data to regional weather forecast has also been demonstrated.

Besides the potential use in 4D assimilation by operational NWP, scatterometer data have been widely used by marine weather and hurricane centers in analyzing and predicting marine storms. For most of the Atlantic hurricanes in 1999, closed circulation with intensity meeting the criteria of a tropical depression were observed by QuikSCAT up to a few days before their identifications by the National Hurricane Center. QuikSCAT data were used to track the surface vortex of Hurricane Floyd all the way back to the African coast five days before it was identified as a tropical depression east of the West Indies. Because such vortices, in their early stages, are too small to be resolved by operational NWP products, and have no clear cloud signal, the scatterometer, with its high spatial resolution, is the best means (if not the only means) to study these early vortices, their tracks across the Atlantic, and their evolution into full-blown hurricanes.

Oceanographers, who were in great need of information on wind forcing of ocean circulation, were the first group to support space-based scatterometer missions. One of the applications is to use scatterometer winds to force ocean general circulation mode. Many studies show that winds from scatterometer are superior in forcing more realistic oceanic responses in the models than NWP winds.

Since scatterometer winds have become continuously available, they have been used in studies of seasonal phenomena like the Monsoons and interannual signals like El Nino Monsoons are the seasonal change of wind forced by the temperature contrast between the continent and the ocean. Scatterometer winds have been used to study oceanic responses to the changes of monsoons in the South China Sea and the Arabian Sea. They have been used to study the influence of moisture advection on continental precipitation in China, Africa, and South America.

El Niño and Southern Oscillation (ENSO), the strongest interannual climatic signal, is believed to be associated with the collapse of the Pacific trade winds. Scatterometers have revealed, with unprecedented resolution, the evolution of the tropical wind systems associated with ENSO. Model initialization with scatterometers winds have been shown to improve El Nino forecast. Scatterometer winds have been to use link the ocean warming in the equatorial Pacific during an El Nino to intraseasonal wind surge in the western Pacific and modification of decalal phenomena in the North Pacific.

The high resolution allows studies of small coastal jets and eddies and derivative parameters, such as atmospheric convergence. Scatterometer winds were used to study oceans response to the wind jets coming out of the mountain gaps near Vladivosktok and Central America. For the first time, the cyclonic circulation of the small Catalina Eddy, which brings ocean-cooling effect to Los Angeles, was visualized by scatterometer winds. A zonal convergence zone south of equator, running eastward from Brazil is also revealed for the first time with scatterometer data.

The broad coverage reveals new phenomena in data-poor tropical and southern oceans. By combining observations of QuikSCAT and Tropical Rain Measuring Mission (TRMM) a narrow break in the westward Trade winds and North Equatorial Currents system was found stretching over 2000 miles from the Hawaii Islands to the western Pacific. It consists of eastward current, warm water, atmospheric convergence, and positive curl of wind stress; the system was revealed as a whole for the first time. The system is postulated to be triggered by the Hawaii Islands but sustained by positive ocean-atmosphere feedback. Using QuikSCAT and TRMM the coherent and in-phase propagation of sea surface temperature and wind vectors in the Tropical Instability waves in the eastern equatorial Pacific was studied.

Measurements from merchant ships and weather stations are extremely sparse in the hostile environment around Antarctica where strong winds circulate around the globe over open oceans. Scatterometer data were used to study wind forcing of the circumpolar current. Scatterometers are capable of monitoring both the Antarctic sea ice extent (SIE) and the wind field over adjacent oceans at the same time, making it possible to characterize the joint variabilities of both wind and ice. Scatterometers observe a wavenumber-3 pattern in the wind, which coincides with three SIE maxima. The wind and ice patterns move together eastward during the winter season. The SIE maxima also provide favorable conditions for storm-generation over the ocean and its has interannual variabilites linked to ENSO.

Wind shear facilitates the turbulent transfer of heat, moisture and gas between the ocean and the atmosphere. The transport is mostly parameterized in terms of wind speed, but there are suggestions that the backscatter measured by the scatterometer contains information on secondary factors, such as small-scale wave fields, on ocean-atmosphere gas transfer, in additional to the information on wind speed. The unique contribution of the scatterometer in ocean-atmosphere exchanges is likely to be in estimating the transport terms in the conservation equation, whether it is the curl of wind stress in oceanic biological pumping or the atmospheric moisture advection in the atmospheric hydrologic balance.

5. Wind Speed Measurements

Both the microwave altimeter and the synthetic aperture radar (SAR) are similar to the scatterometer in the sense that all three are active sensors that send microwave pulses to the Earth's surface and measure the backscattered power. While the scatterometer views at oblique angles, the altimeters view at nadir (very small incident angles). At nadir, the backscattered energy is a result of specular reflection (the wavelets serve as small mirrors), and the backscatter is not sensitive to wind direction. Because the instrument is not scanning, data are only available at a very narrow repeated ground-tracks. The coverages of all the past altimeters are poor compared with the scatterometer and the microwave radiometers. Altimeters were flown on Seasat and ERS spacecraft described in Section 3. Geosat, which was in operation between 1985-1989 and Topex-Poseidon, which was launched 1992, are two missions dedicated to the altimeter.

The same model function used to retrieve winds from scatterometer can be used for SAR. But, a SAR looks perpendicular to aircraft path only at one azimuth angles, and cannot resolve wind direction like the scatterometer. The main objective of SAR is to provide high resolution imaging of the Earth's surface. SAR has spatial resolutions that are much better than scatterometers, but the high resolution also introduce higher uncertainties in accuracy caused by secondary effects that affect surface roughness. The instrument and the data processing procedure are much more complicated than the scatterometer and there have been severe calibration problems. Both the SAR on Seasat and ERS have spatial resolution of 30m and swath width of 100 km. The narrow swath width and the sporadic operation prevent global monitoring of ocean surface wind. Radarsat-1, which was launched in 1995, can operate in the scanning mode with a spatial resolution of 100 m and a 500-km wide swath; this instrument is the closest to provide continuous global coverage.

Ocean surface wind speed can also be derived from the radiance observed by microwave radiometer. It is generally believed that wind speed affects the surface emissivity indirectly through the generation of ocean waves and foam. Radiometers designed to observe the ocean surface operate primarily at window frequencies, where atmospheric absorption is low. To correct for the slight interference by tropospheric water vapor, clouds, and rainfall and, to some extent, the effect of sea surface temperature, radiances at frequencies sensitive to sea surface temperature, atmospheric water vapor, and liquid water are also measured.

Microwave radiometry has much longer history than the active microwave sensors. Ocean surface wind speeds were derived from the Scanning Multichannel Microwave Radiometer (SMMR) on Seasat and Numbus-7 launched in 1978. A major improvement in wind speed availability was made by the Scanning Multichannel Microwave /Imager (SSM/I), the first of which was launched in 1987 on the spacecraft Defense Meteorological Satellite Program (DMSP). Several DMSP satellites with SSM/I on board have been in orbit at the same time, providing continuous, global coverage since July 1987.

9. Future Missions and Technology

Quikscat will be followed by an identical scatterometer on ADEOS-2 scheduled to be launched in 2002. If there is sufficient overlap between the operations of the two identical scatterometers, the importance of high frequency and high wave-number wind forcing on the ocean can be demonstrated. ESA is scheduling to launch a series of C-band dual-swath advance scatterometers (ASCAT), on their operational platform METOP, starting in December 2005. NASA is planning to launch a polarimetric scatterometer on the Japanese Global Change Observation Mission (GCOM), so that two wide-swath scatterometers will provide continuous time series of high frequency wind forcing.

The Naval Research Laboratory is scheduled to launch the Windsat mission to test the capability of a polarimetric microwave radiometer in measuring ocean surface wind vector in early 2003. Conventional microwave radiometer measures surface radiance at horizonal and vertical polarization. Preliminary studies indicate that measurement of the coherence between vertically and horizontally polarized radiance will provide directional information of surface winds.

One of the drawbacks to scatterometry is the wind-direction ambiguity. The backscatter is a cosine function of the azimuth angle. In a recent experiment, it was demonstrated the correlation between co-polarized and cross-polarized backscatter is a sine function of azimuth angle. By adding a receiver of cross-polarized backscatter to the scatterometer on QuikSCAT, the directional ambiguity problem can be mitigated. A polarized scatterometer is planned of GCOM.

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Key Words

Air-sea interaction, Wind, Current, Waves, Monsoon, El Niño, Weather-prediction, Storm, Tropical-cyclone, Sea-ice, Remote-sensing, Climate-changes, Satellite, Coastal-ecology

Further Reading

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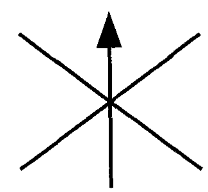
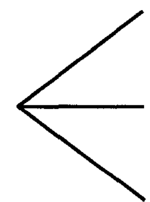
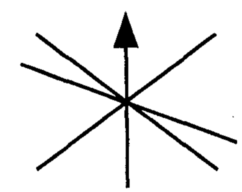
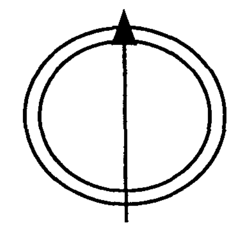
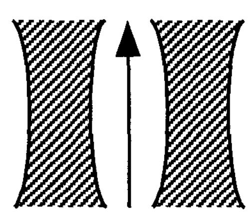
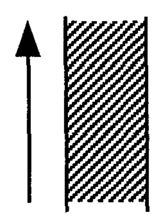
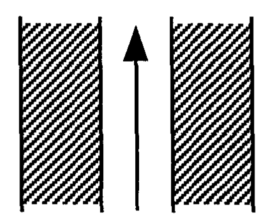
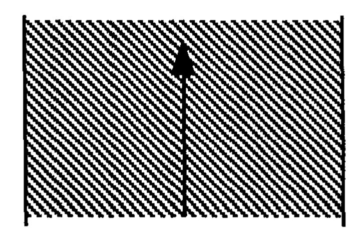
Spaceborne Scatterometers

	SEASAT	ERS-1/2	NSCAT	QuikSCAT
Frequency	14.6 GHz	5.3 GHz	13.995 GHz	13.402 GHz
Scan Pattern				
Polarization	V-H, V-H	V ONLY	V, V-H, V	V, H
Inc. Angle	22°-55°	18°-47°, 24°-57°	18°-57°, 22°-63°	46°, 54°
Beam Resolution	Fixed Doppler	RANGE GATE	Variable Doppler	Spot
Resolution	50 km	50 km	25 km	25 km
Swath	500 km 500 km 	500 km 	600 km 600 km 	1800 km 
Daily Coverage	Variable	41%	77%	93%
Dates	6/78 – 10/78	8/91-1/01	8/96 – 6/97	6/99 +